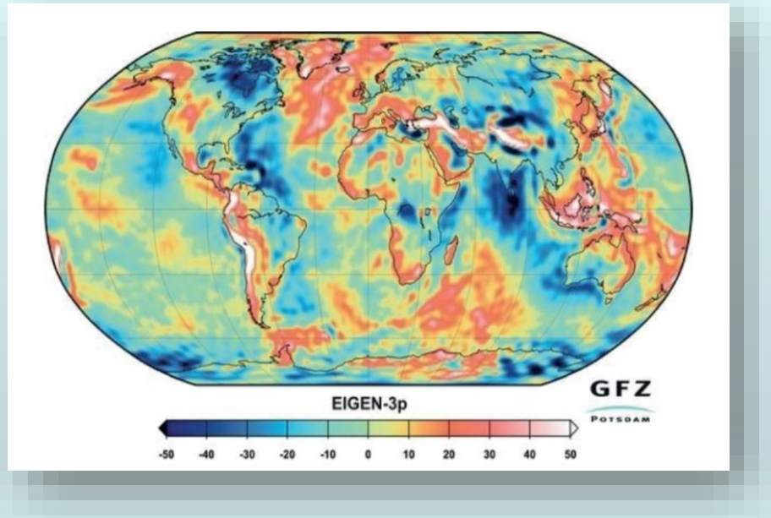
Development of a cold-atom inertial measurement unit

J.Bernard[1,2], I.Perrin[1], Y. Bidel[1], M. Cadoret[1,2], N. Zahzam[1], C. Blanchard[1] and A. Bresson[1]

[1] DPHY, ONERA, Université Paris Saclay, F-91123 Palaiseau, France
[2] LCM-CNAM, 61 rue du Landy, 93210, La Plaine Saint-Denis, France

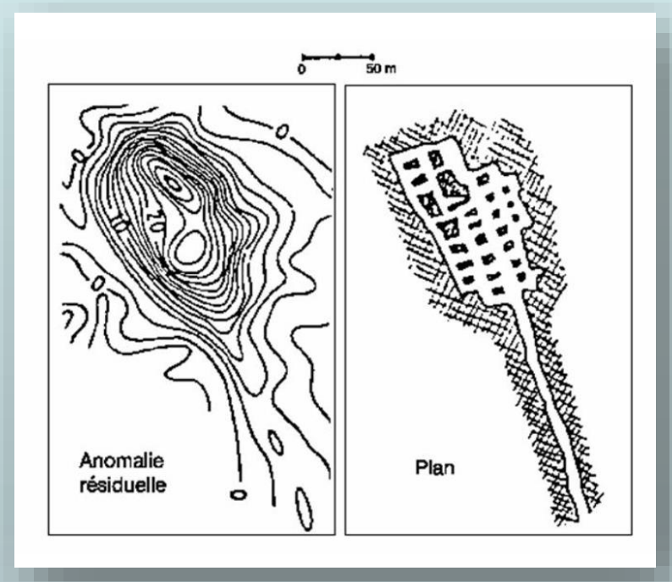
Application of inertial sensing



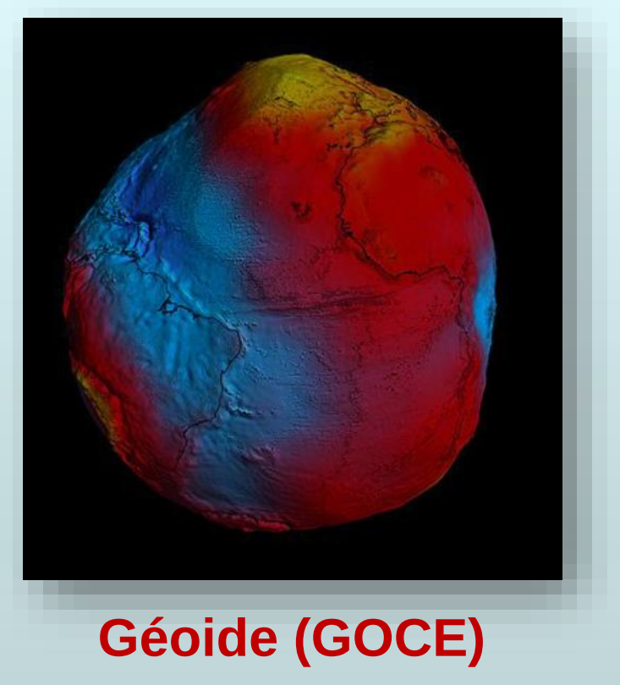
Gravity anomaly (CHAMP)

Navigation

(inertial navigation, gravity field mapping)



Montreal harbour mapped by gravity measurement



Géoide (GOCE)

Geophysics

(internal structure of Earth, seismology)

Sub-surface detection

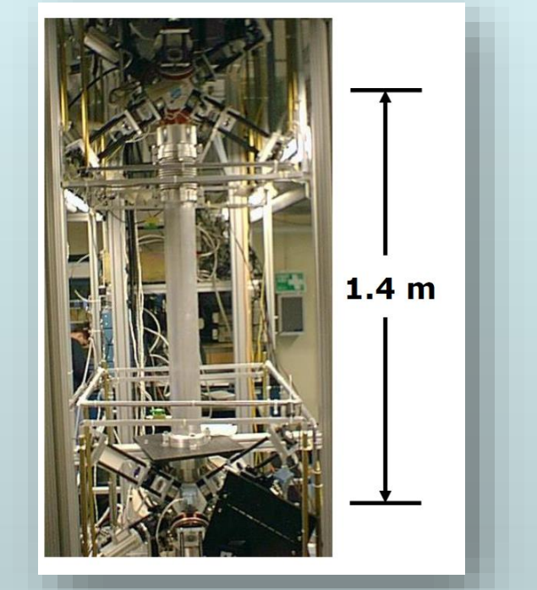
(archeology, oil prospection)

Fundamental Physics

Equivalence principle

ICE (SYRTE, LP2N)

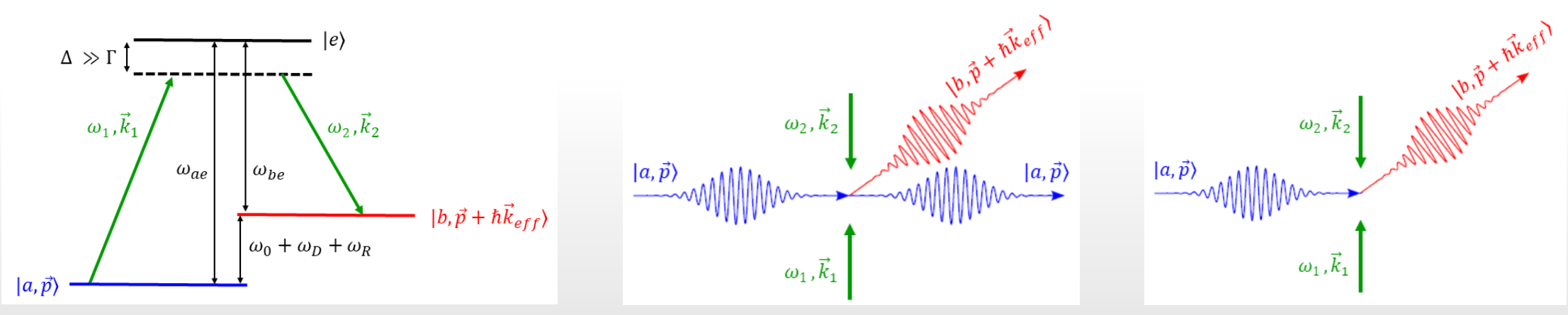
Determination of G



Cold-atom gradiometer (Stanford University, M. Kasevich)

Atom interferometry

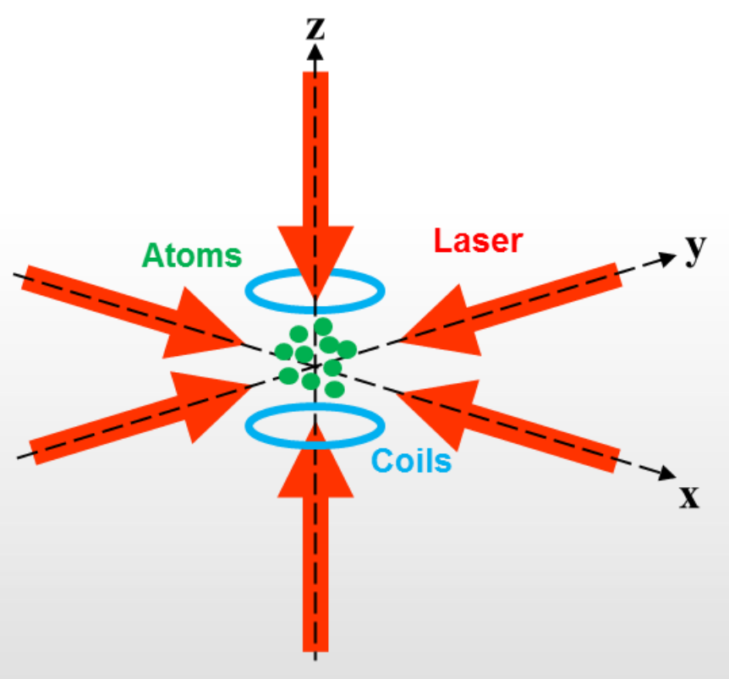
Stimulated Raman transitions



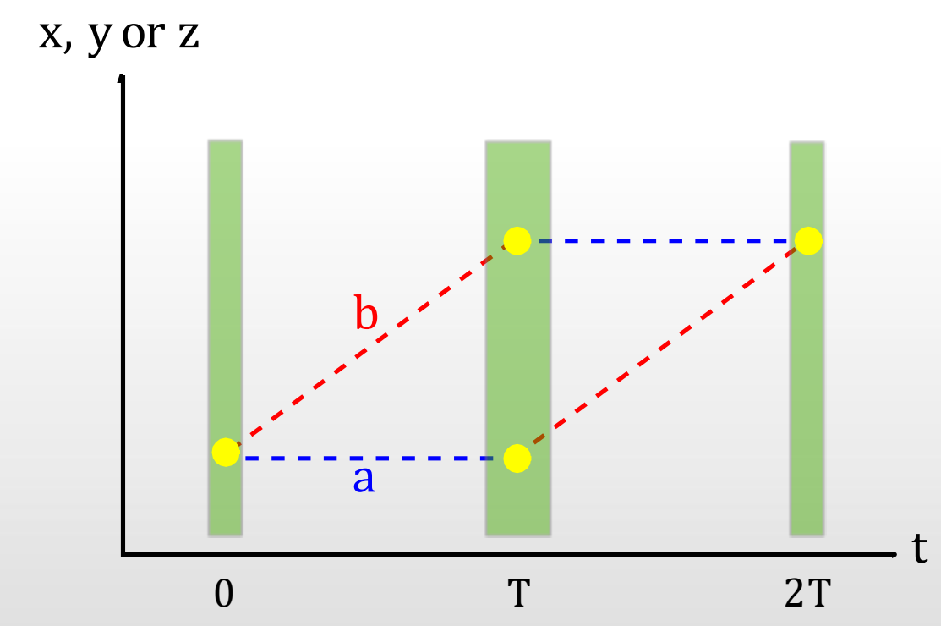
2 atomic states a and b — $\frac{\pi}{2}$ pulse : beamsplitter — π pulse : mirror

Analogue of Mach-Zehnder optical interferometer :
light ↔ matter waves ; mirrors and bs ↔ $\frac{\pi}{2}$ and π pulses

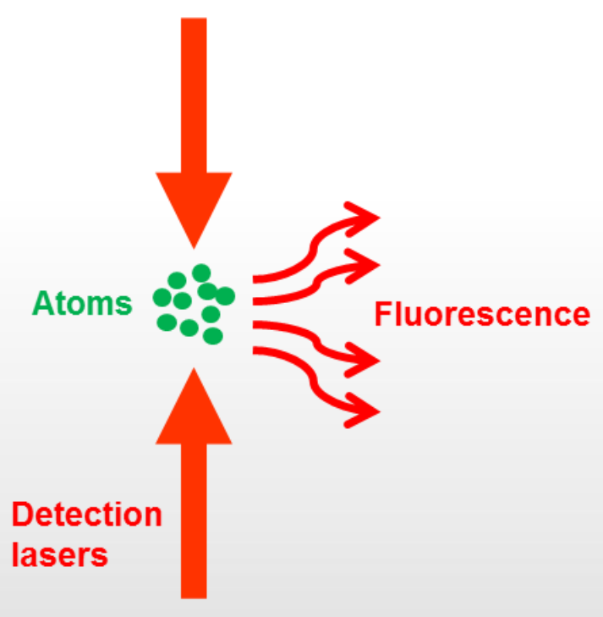
Atom interferometry principle



1. Magneto-optical trap



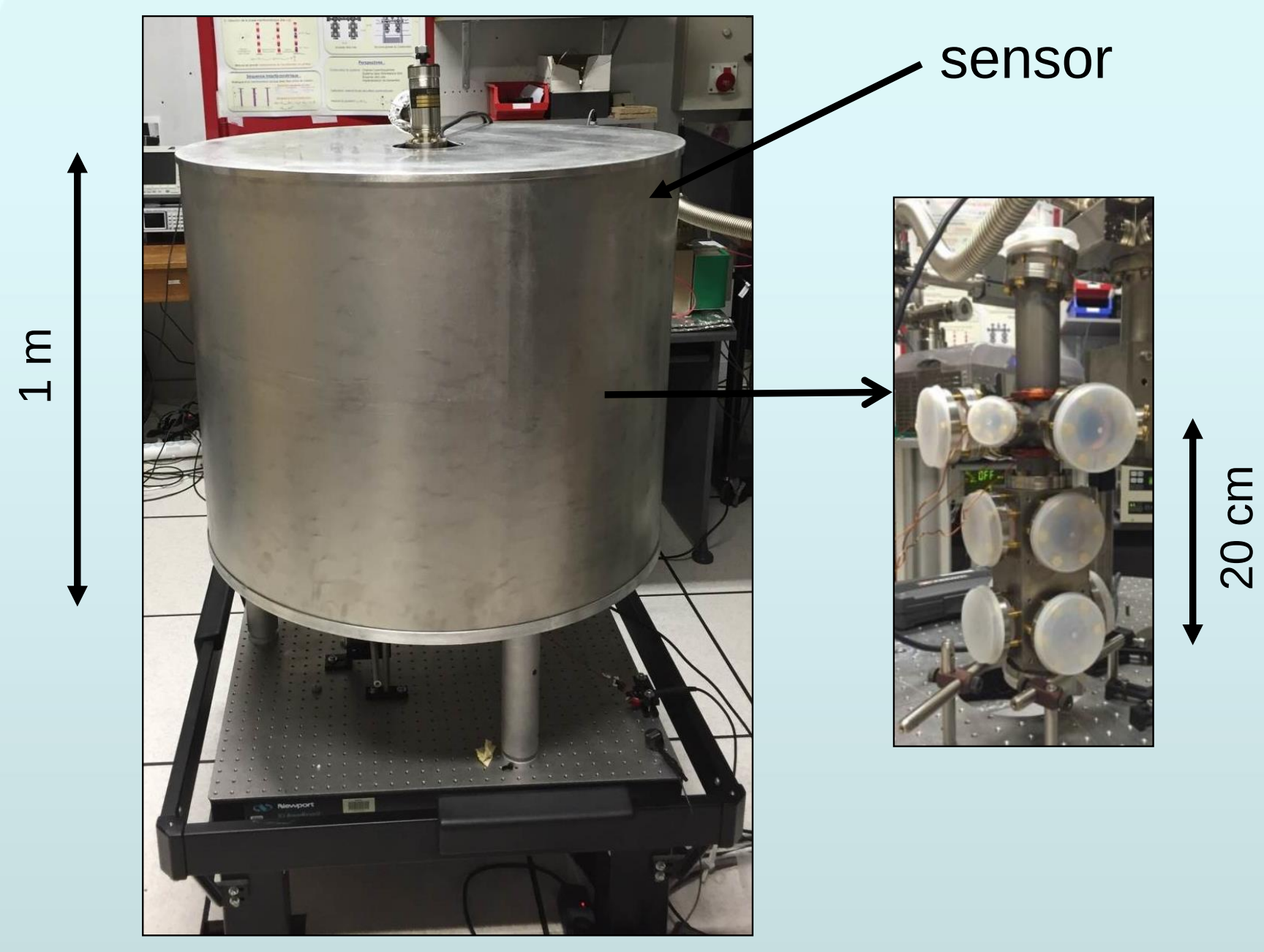
2. Mach-Zehnder light-pulse atom interferometer using stimulated Raman transitions



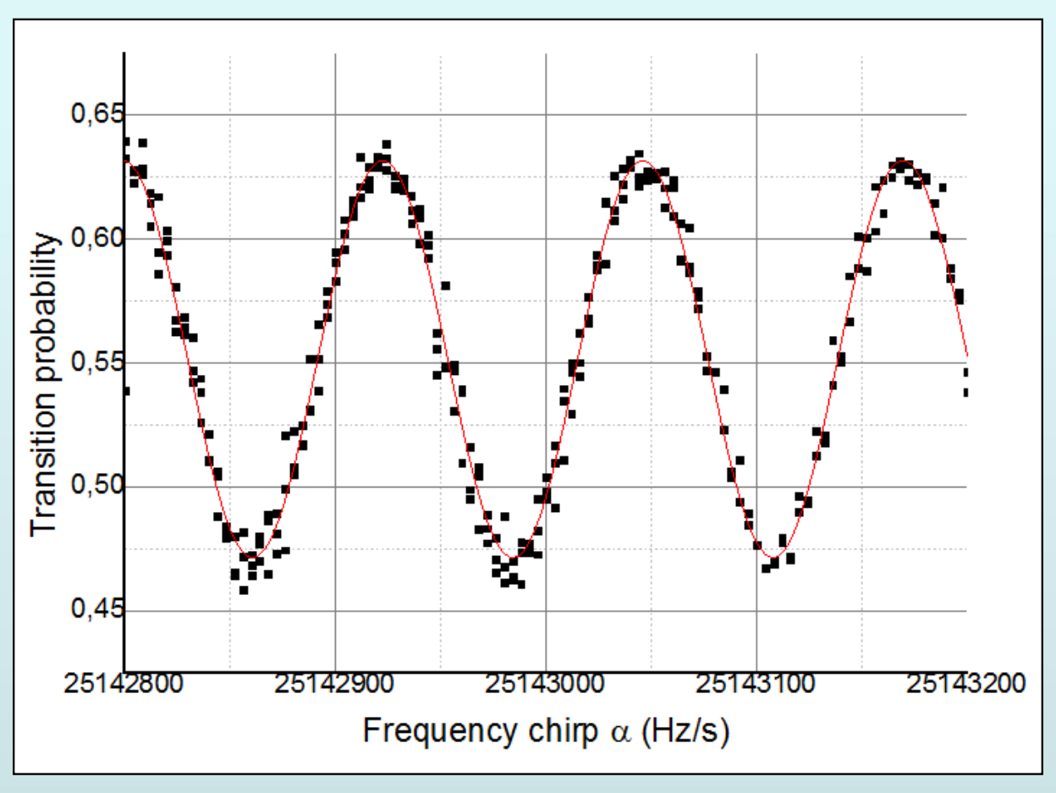
3. Detection of the interferometer phase :

$$\Delta\phi = \vec{k}_{\text{eff}} \cdot \vec{a}\, T^2$$

Inertial sensor



Gravimetry fringes



$$P = P_0 - \frac{C}{2}\cos(\Delta\phi)$$

Atomic gravimeter and gradiometer already successfully implemented

- Atoms preparation : 10^7 atoms of ^{87}Rb trapped in the hyperfine state $|a\rangle = |F = 1, m_F = 0\rangle$ laser-cooled at 2 μK
- Raman frequency is chirped to compensate for the Doppler effect :

$$\Delta\phi = (\vec{k}_{\text{eff}} \cdot \vec{a} - 2\pi\alpha)\, T^2$$

Goal

To measure the 3-axis components of acceleration and rotation in a compact inertial sensor for onboard applications

Horizontal acceleration measurement

Frequency chirped Raman lasers

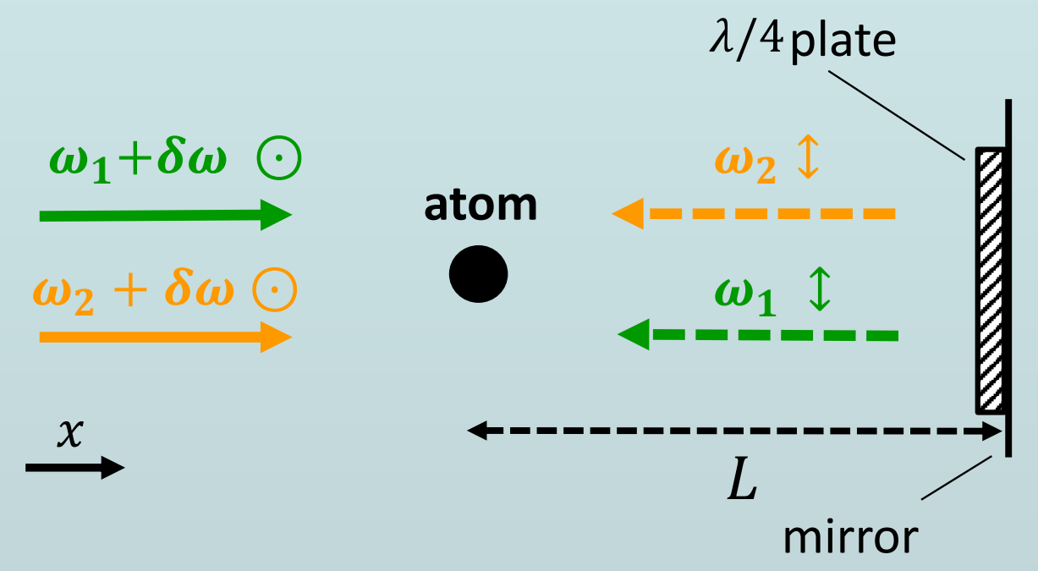
- Detuning from the two-photon resonance :

$$\delta = \omega_1 - \omega_2 - (\omega_0 + \omega_D + \omega_R)$$

ω_0 = hyperfine transition
$\omega_R = \frac{\hbar k_{eff}^2}{2m}$ = recoil frequency shift
$\omega_D = \pm\vec{k}_{eff} \cdot \vec{v}$ = Doppler effect

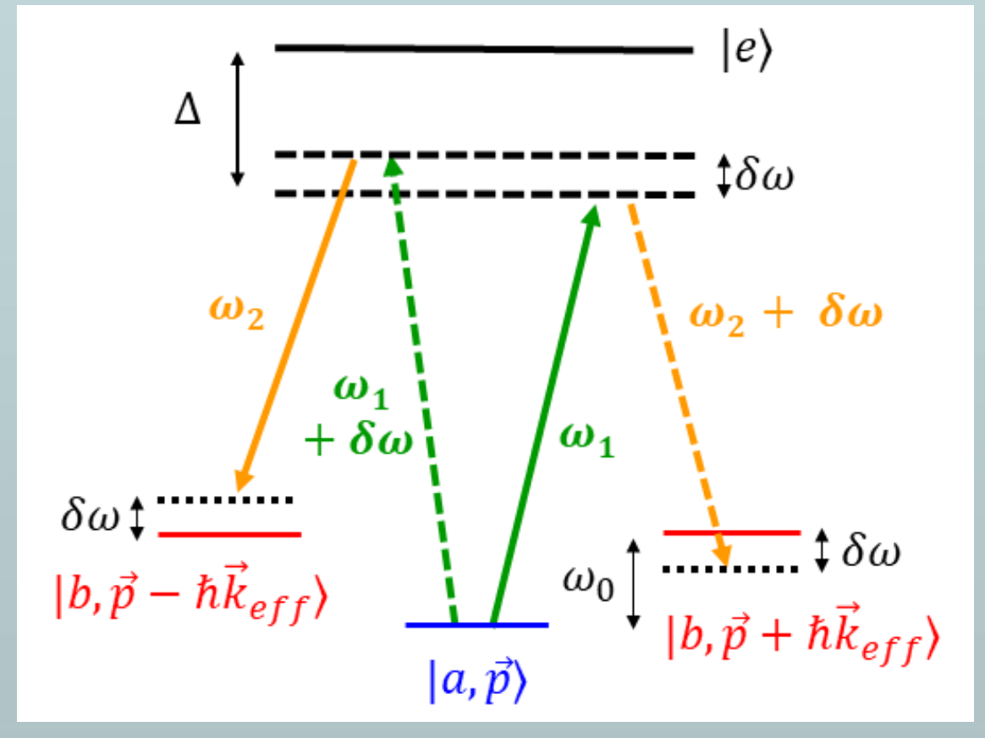
- No Doppler effect for zero-velocity atoms :
  2 pairs of Raman lasers simultaneously resonant and coupling $|a, \vec{p}\rangle \rightarrow |b, \vec{p} \pm \hbar\vec{k}_{eff}\rangle$

⟶ Frequency chirp applied on the Raman lasers to lift the degeneracy : $\beta = \frac{1}{2\pi}\frac{d\omega_{1/2}}{dt}$

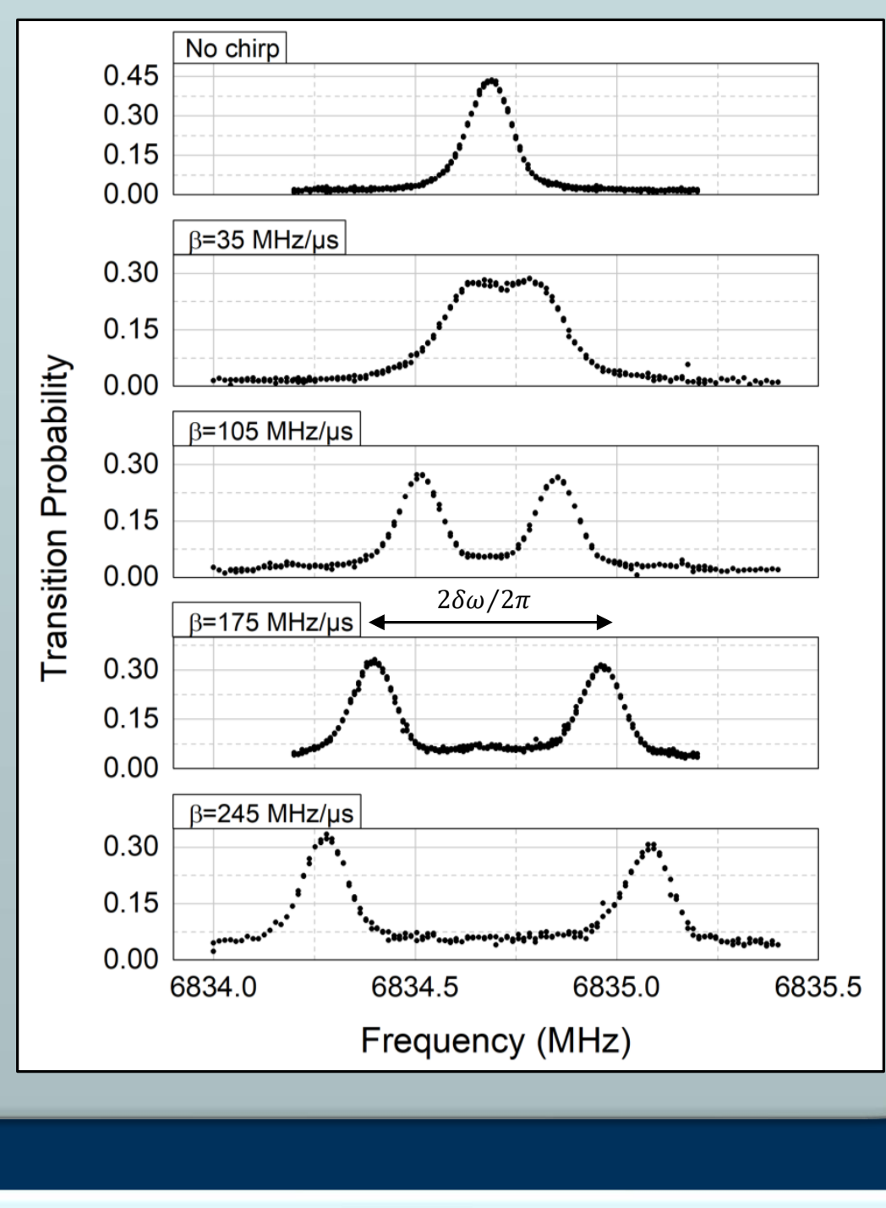


Mimics an effective atomic velocity in the reference frame of the lasers : equivalent Doppler shift

$$\omega_D = 2\pi\beta \cdot \frac{2L}{c} \equiv \delta\omega$$



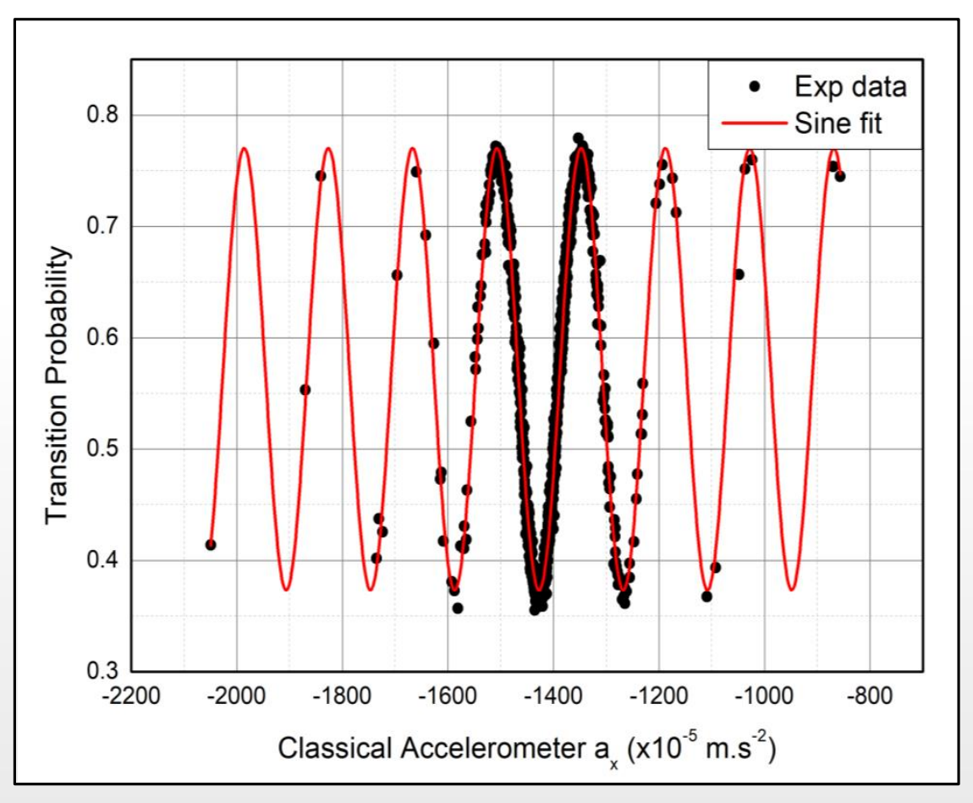
Raman Spectroscopy



I. Perrin, J. Bernard, Y. Bidel, A. Bonnin, N. Zahzam, C.Blanchard, A. Bresson, and M. Cadoret, ***Zero-velocity atom interferometry using a retroreflected frequency-chirped laser,*** Phys. Rev. A 100, 053618 (2019).

Results

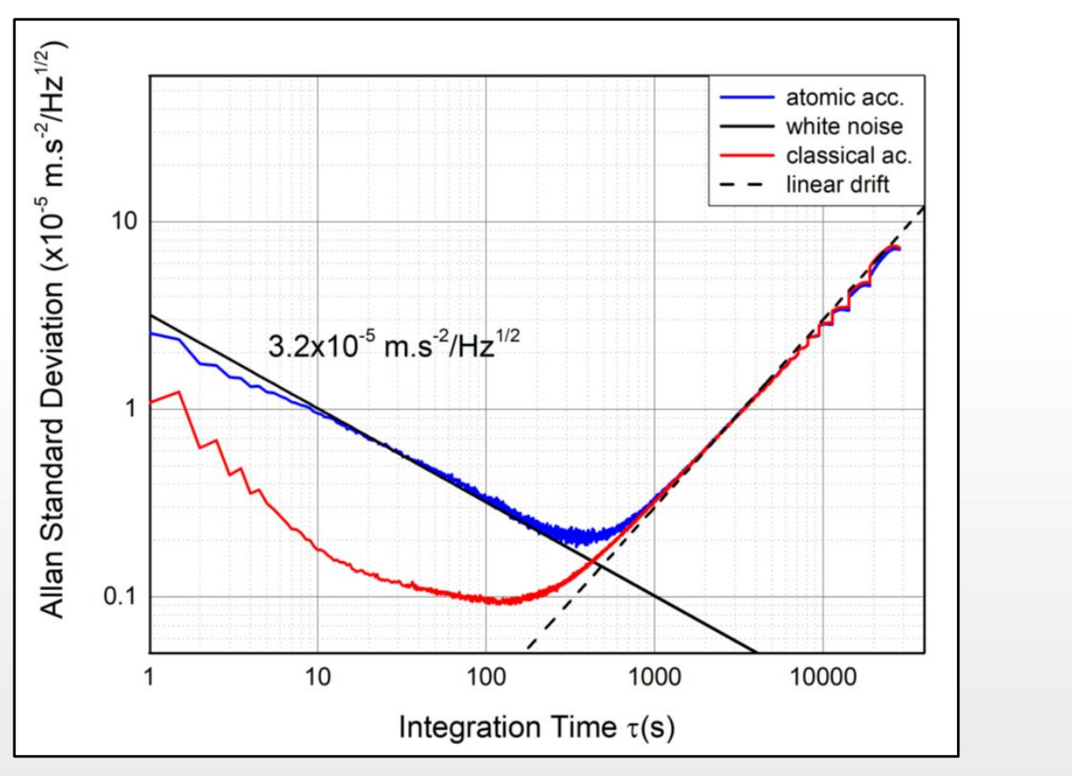
Correlation fringes



$\frac{\pi}{2} - \pi - \frac{\pi}{2}$ horizontal interferometer

- Chirped-Raman pulse sequence with $\beta = 210\ \text{MHz.}\,\mu\text{s}^{-1}$
- Classical correlations : $P = P_0 - \frac{C}{2}\cos(\Delta\phi)$ with $\Delta\phi = \vec{k}_{\text{eff}} \cdot \vec{a}\, T^2$

Sensitivity and stability

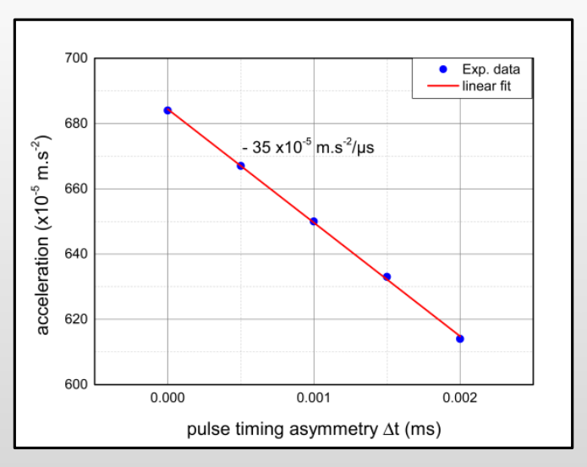


Hybridization of a classical accelerometer with the atom accelerometer

- Short-term sensitivity : $3.2 \times 10^{-5}\ \text{m.s}^{-2}/\sqrt{\text{Hz}}$
- Best resolution at 500s integration time : $0.2 \times 10^{-5}\ \text{m.s}^{-2}$
- Drift possibly due to an angular variation of the Raman mirror ($\sim 10\ \mu\text{rad}$)

Theoretical and experimental bias study

- Chirp technique insensitive to :
  - Raman lasers intensity variations
  - Raman pulses duration
  - value of the chirp β used to lift the degeneracy
- Bias induced by :
  - Raman pulse timing asymmetry (simulated Doppler term – clock effect – bias $= 35 \times 10^{-5}\ \text{m.s}^{-2}/\mu s$)
  - effective wave vector changes during the AI sequence



- For the resulting biases to be $\leq 10^{-5}\ \text{m.s}^{-2}$, the time sequence (pulse and frequency ramp triggering) must be controlled at 30 ns.